Exploration of Composites Processing and Producibility by Analysis

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Presented at
The 34th International SAMPE Technical Conference Baltimore

November 2002

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **NOV 2002**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Exploration of Composites Processing and Producibility by Analysis**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boeing Phantom Works**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**32**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Acknowledgements

Jointly accomplished by a BOEING Led Team and the U.S. Government under the guidance of NAST

Work funded by DARPA/DSO and administered by NAST through TIA N00421-01-3-0098

Acknowledge the support of Dr. Steve Wax and Dr. Leo Christodoulou of DARPA/DSO

Also:
Gail Hahn (PM), Charley Saff (DPM), & Karl Nelson (DPM) - Boeing Corp.

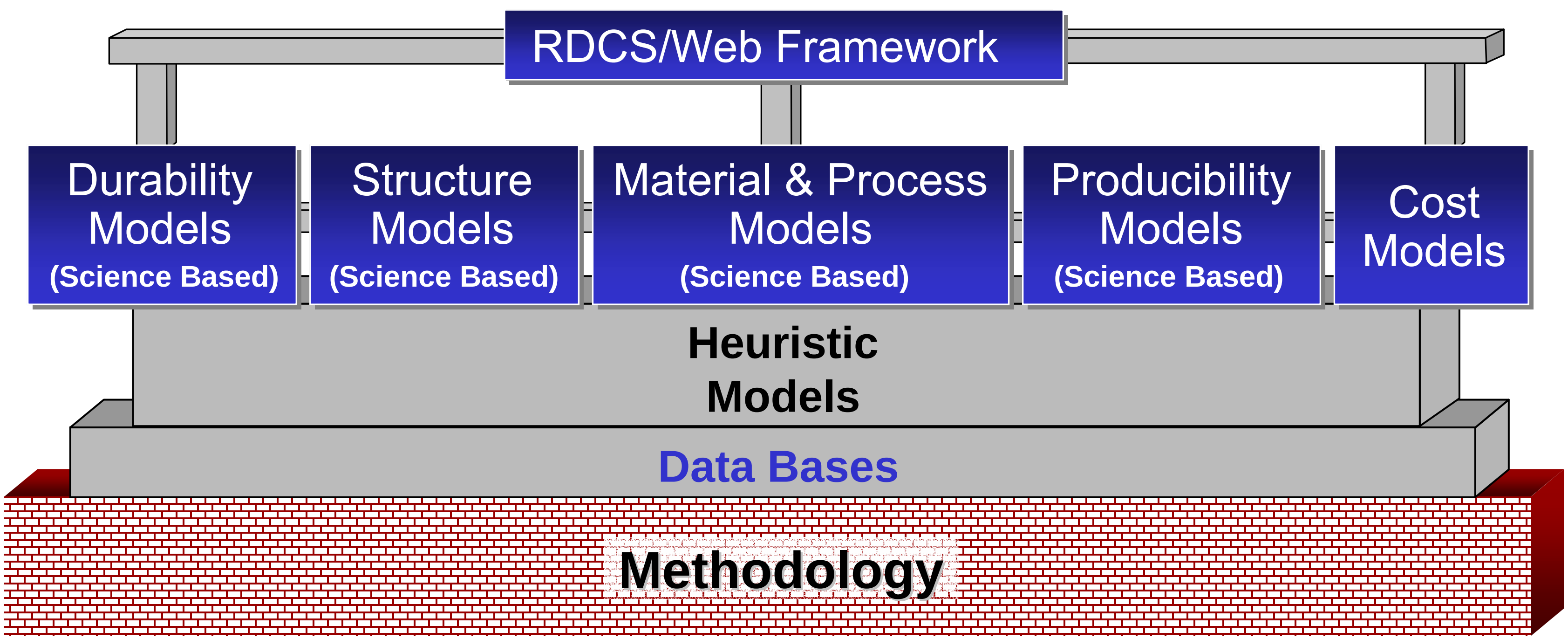
AIM-C Team - Boeing (St. Louis, Seattle, Canoga Park, Philadelphia), Northrop Grumman, Materials Sciences Corporation, Convergent Manufacturing Technologies, Cytec Fiberite, Inc, Massachusetts Institute of Technology, Stanford & NASA (Langley)

Outline

- Background
  - –Accelerated Insertion of Materials – Composites (AIM-C)
  - –Robust Design Computational System (RDCS)
- Purpose and Objectives
- Problem Description
- Computational Approach
- Results
- Summary
- Future Work

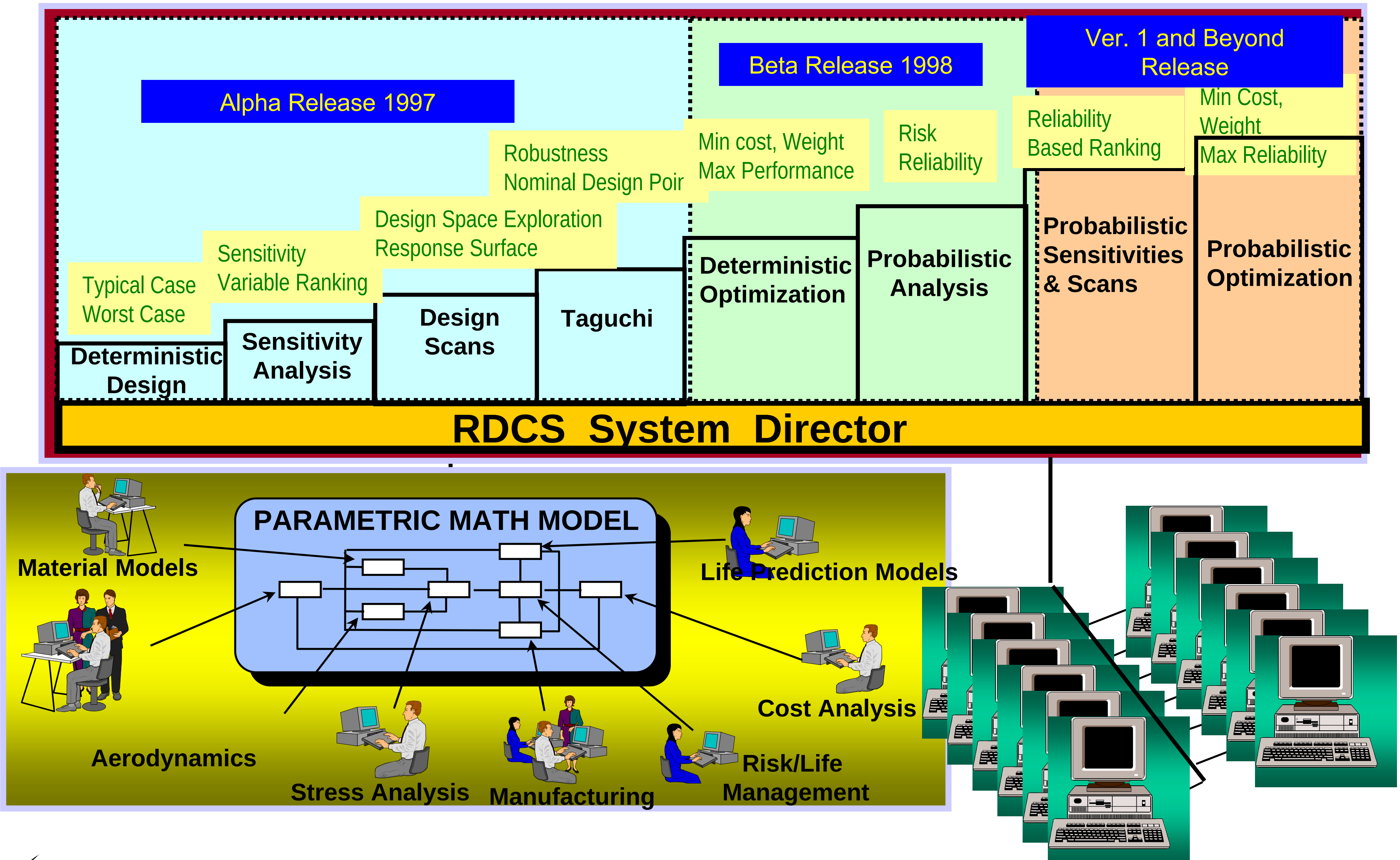
BACKGROUND
The AIM-C Plan

- Incorporate methodology into an interface that guides the user and tracks the progress of technology maturation to readiness
- Deliver software in steps toward a useable system as analysis modules are completed
- Demonstrate capability through system validation, compelling technical demonstration, and a ‘blind validation’ to insure usability



RDCS – Robust Design Computational System

BACKGROUND
RDCS Tool An Instance of Modern Design Framework



Purpose and Objectives

Purpose:

- Utilize an RDCS driven feature based parametric processing model for producibility assessments through the web based front-end of the producibility module

Objectives:

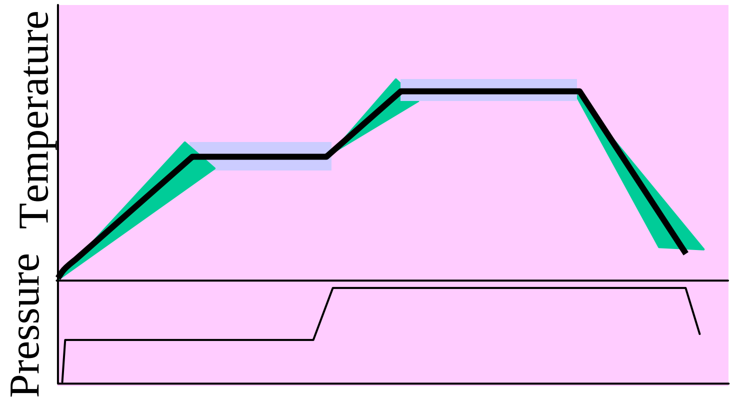
- Illustrate parameterization of process module
- Show current stage of module development
- Highlight integration issues and direction of work
- Demonstrate feature based parameterized producibility assessment

Approach:

- Parameterize geometry inputs to Processing Module based on use scenario for a Producibility Assessment. Exercise with RDCS tools through linkage with producibility module.

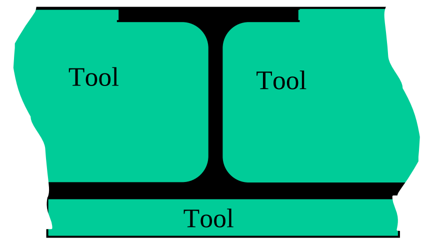
Use Scenario and Problem Statement

Composite System Cure Requirements

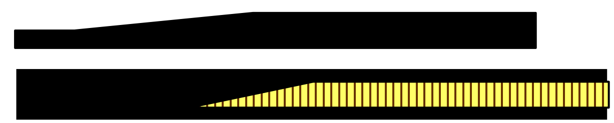


- Resin chemistry requirements
- Consolidation requirements
- In-cure and residual stresses
- Minimum and maximum rates
- Minimum and maximum hold times
- Intermediate temperature holds

Design and Tooling Requirements



Thermally massive tooling, inserts
Co-Cure Structure, Lug Plates

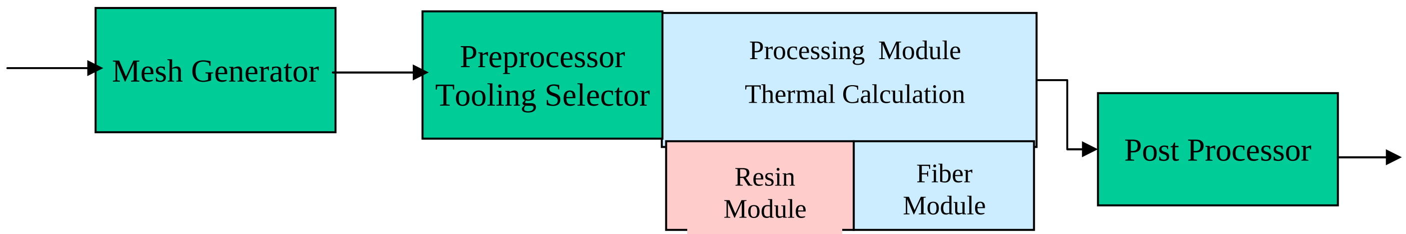


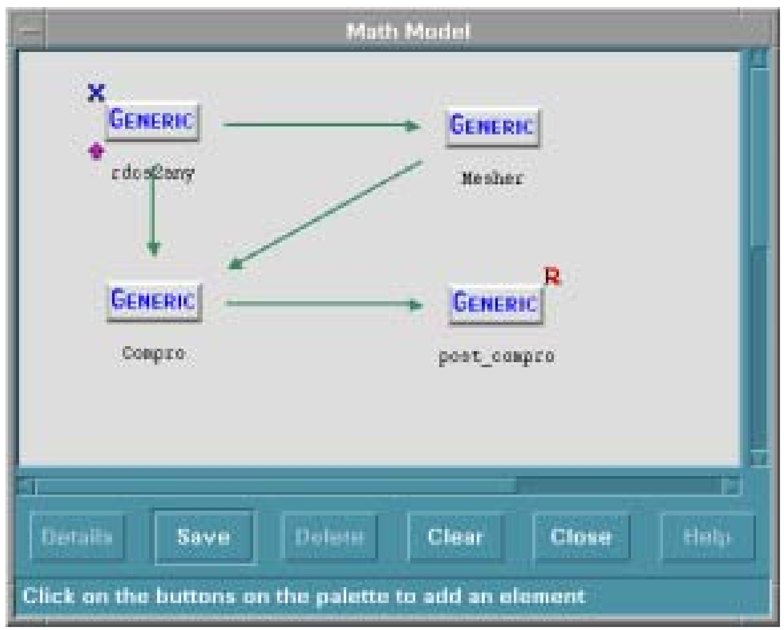
Thick and Thin Sections
Keel beams, Attachment points

Combinations of Above

Evaluate Design Driven Requirements Relative to Material and Processing Requirements for Heat-up Rate and Exotherm Producibility Issues

Simulation Integration Structure

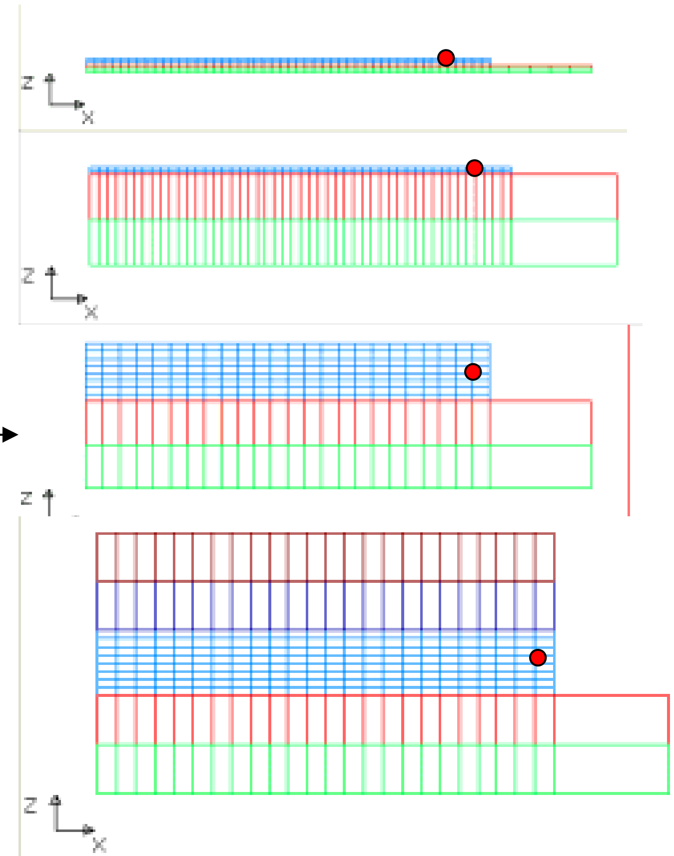




Parametric flat panel mesh generator

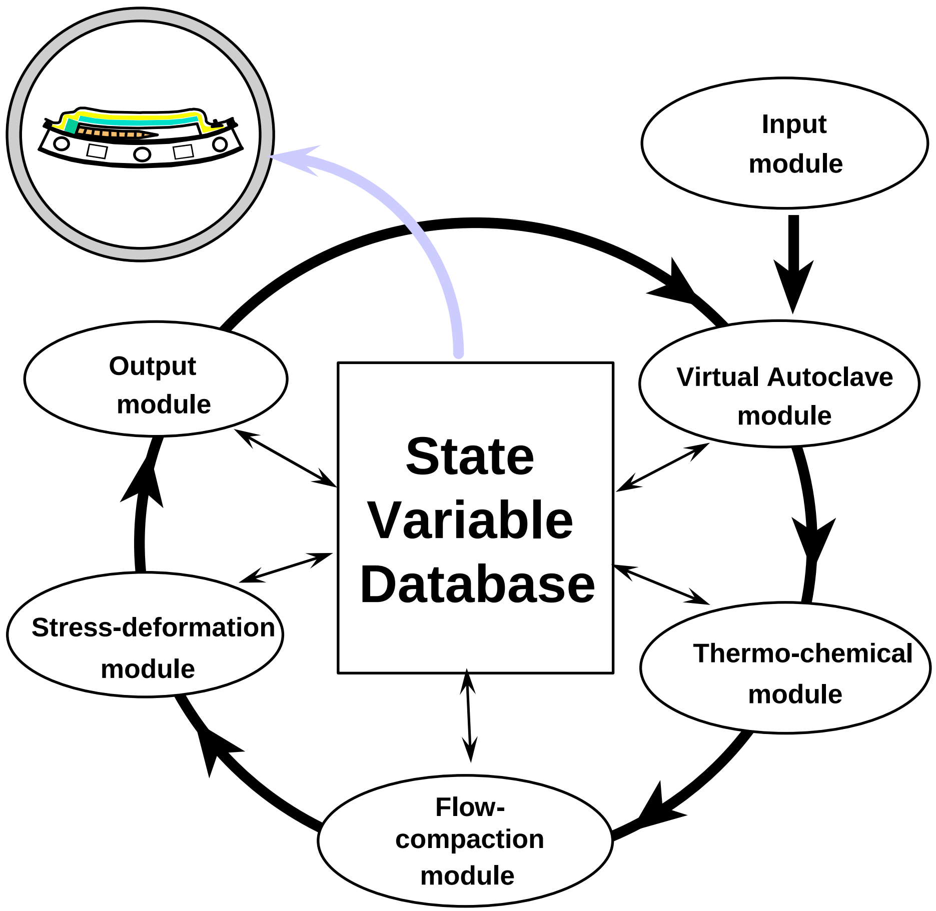
Part	Tool	Top Tool
0.25”	3.00”	0”
2.00”	3.00”	3.00”
0.25”	3.00”	3.00”

Mesh Generator



- Virtual Thermocouple for Autoclave Control
  Assigned to mesh by preprocessor

Processing Module Description



- Part/Tool Geometry
- Process Cycle
- Autoclave Characteristics
- Material Behaviour

- F.E. Description
- Autoclave Simulation
- h = f (P,T)
- Material models

- Temperature, Resin Degree of Cure, volume fraction
- Part Thickness Profile
- Part Deformations
- Residual Stress

Based on CMT's COMPRO Simulation Software

Input/Output requirements

Parametric Feature Inputs

	Input Requirement	Units	Min.		Max.	Variable Type
G	Part Thickness	Inches	0.25		2	User Entered
H	Top Tool Thickness (3)	Inches	0		3	User Entered
I	Tool Thickness	Inches	0.50		3	User Entered
J	Tool Material (5)		Invar <1>	Aluminum <2>	Composite <3>	User Entered
K	Autoclave Pressure	Psi	45	85	125	User Entered

Autoclave Pressure Input

•As required for consolidation as determined through experimentation

Tool Material Input for Preprocessor

•Integer value output from producibility to RDCS

•Integer value to data set in preprocessor

Input/Output requirements

Process bounds for exploration in RDCS

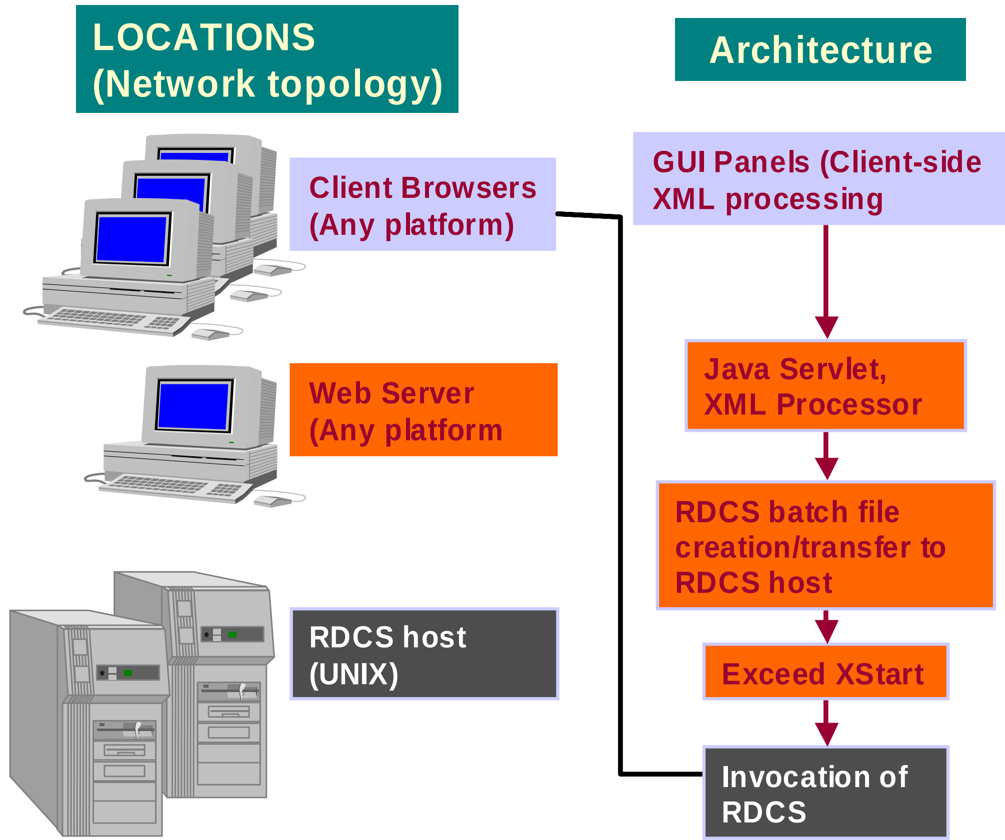
	Input Requirement (Process Bounds)	Units	Demo Min.	Demo Max.	Variable Type
L	Heat Transfer Coefficient (1) (2)	BTU/h.ft^ 2.F	3	7	Independent Process Noise Variable
M	Ramp1 Rate (air)	F/min	2	10	Independent Process
N	Hold 1 Temperature	F	270	290	Independent Process
O	Hold 1 Time (part) (4)	Min	0	120	Independent Process
P	Ramp 2 Rate (air)	F/min	2	10	Independent Process
Q	Hold 2 Temperature	F	355	365	Independent Process
R	Hold 2 Time (part)	Min	360		Independent Process
S	Ramp 3 (air)	F/min	-2	-10	Independent Process

Input/Output requirements

Constraints for RDCS Outputs

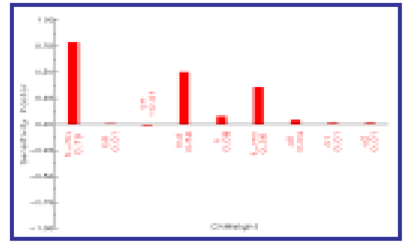
	Input Requirement (Constraints)	Units	Min.	Max.	Variable Type
A	Acceptable part heat up rate	F/min	1	5	Dependent User Entered Constraint
B	Acceptable time at final cure temperature	Minutes	360	380	Dependent User Entered Constraint
C	Resin maximum acceptable Temperature	F	345	365	Dependent User Entered Constraint
D	Maximum acceptable heat up gradient	F	0	50	Dependent User Entered Constraint
E	Maximum acceptable cool down gradient	F	0	50	Dependent User Entered Constraint
F	Resin acceptable cool down rate	F/min	-1.5	-5	Dependent User Entered Constraint

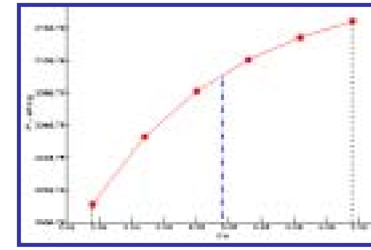
Producibility - RDCS Integration Structure

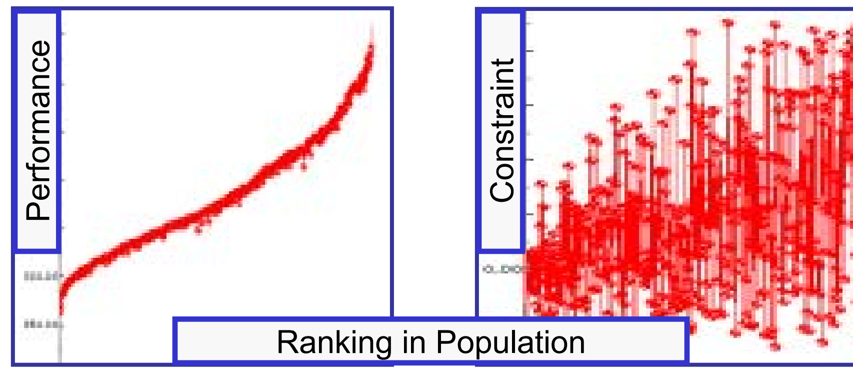


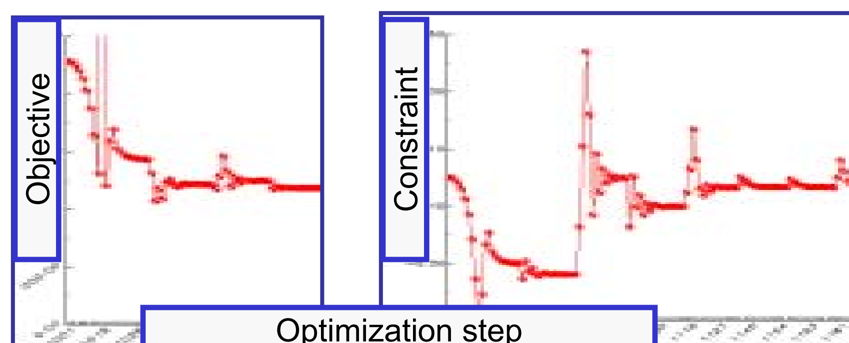
Design Space Exploration Options

- Traditional Design Methods
  - Sensitivity
  - Design Space Scan
- Genetic Algorithm:
  1 - Randomly sample ***entire*** design space
  2 – Evaluate objective and constraints for each design; form performance function
  3 – Swap design variables (traits or “genes”) between the best performing designs to form a new generation; ***go to step 2***
- Gradient based methods:
  Use ***local*** sensitivities of objective and constraint functions to drive the design to an optimal feasible design









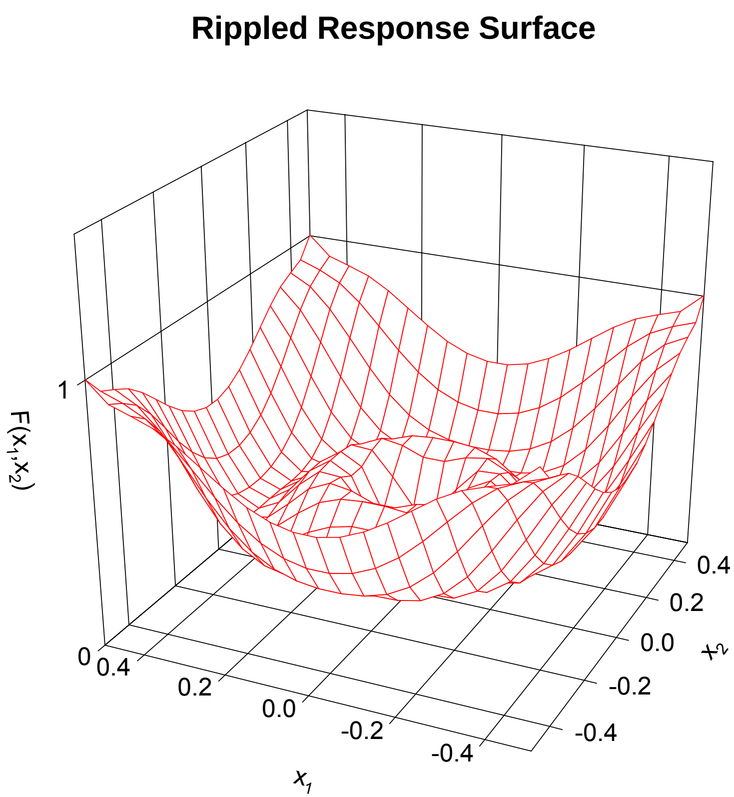
Strategy for Searching a Feasible Cure Cycle

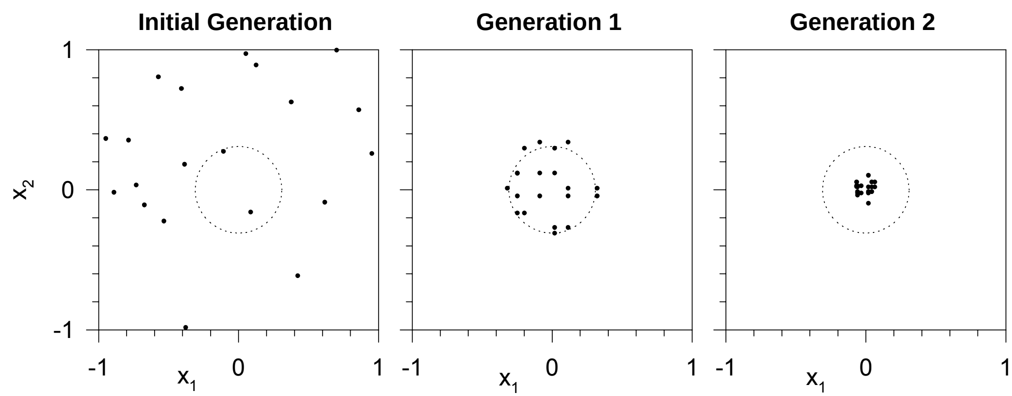
- Design space: 13 variables, 30 responses, 13 constraints
- Strong interaction between variables is expected

- Sensitivity - point information, not suitable for global exploration
- Design space scan
  - Needs off-line post-processing to find feasible designs
  - Partial design space scan won't capture interactions
  - Full factorial is impractical for this many variables (3 levels for each variable ~1.6 million cases)
- Optimization - minimize cure cycle time subject to bounds in design variables and constraints in responses
  - Processing Module results carry some numerical noise (typical for complex numerical problems); Classical gradient based optimizers will fail
  - Genetic Algorithm is an effective solution

Genetic Algorithm Description

Multi-modal objective to test GA





Pattern of successive generation for multi-modal response

Traditional optimizers may fail to find global optimum

Demonstration Cases

	Input Requirement	Units	Case 1	Case2	Case 3.	Case 1A
G	Part Thickness	Inches	0.25	2	2	0.25
H	Top Tool Thickness (3)	Inches	3	0	3	3
I	Tool Thickness	Inches	3	0.5	3	3
J	Tool Material (5)		Composite <3>	Composite <3>	Composite <3>	Aluminum <2>
K	Autoclave Pressure	Psi	85	85	85	85

Challenging Tool and Part Thickness

AIM-C Producibility GUI - Constraint Definition

http://bcp-structurestechnology.rdyne.bna.boeing.com/aimc/index.html - Microsoft Internet Explorer provided by Boeing Canoga Pa

Address http://bcp-structurestechnology.rdyne.bna.boeing.com/aimc/index.html Go

File Edit View Favorites Tools Help

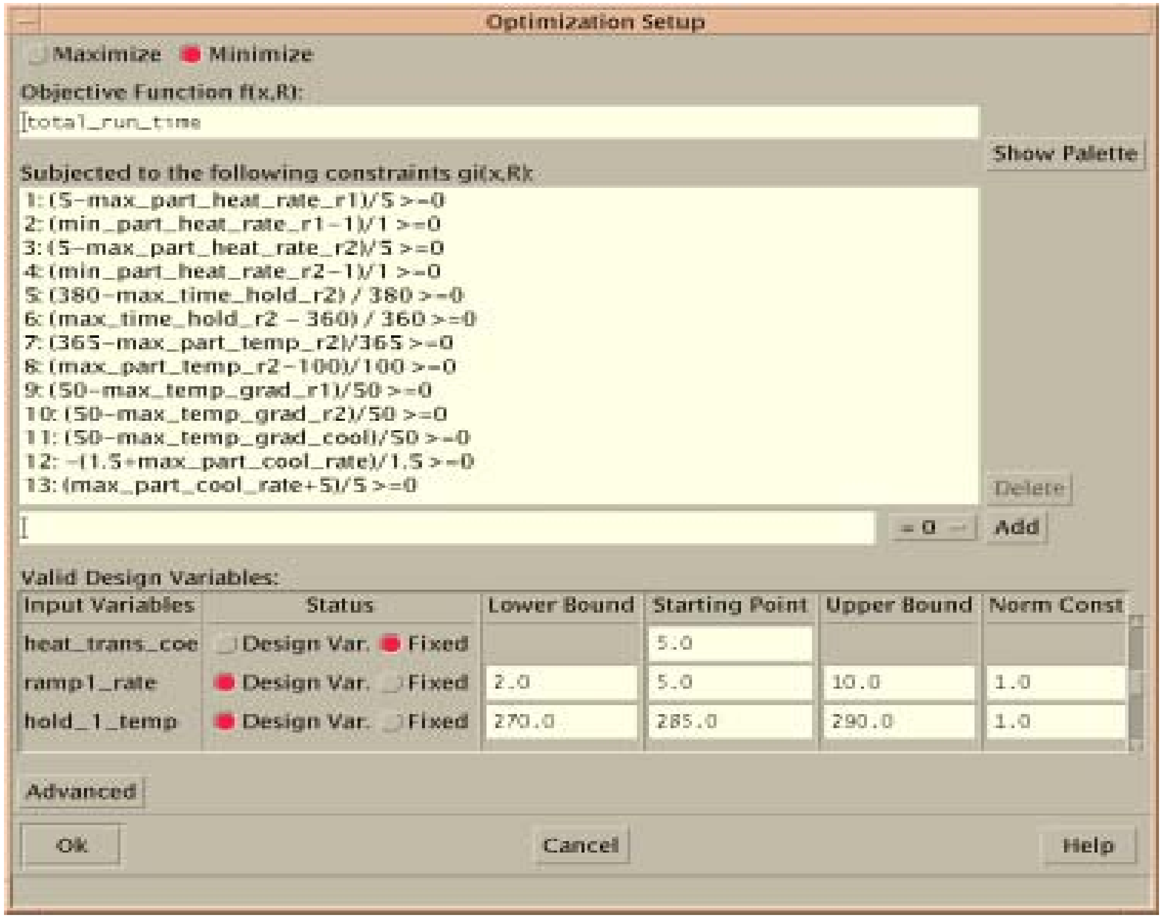
Constraints

Description	Limit.	Hard Limit.	Unit
Minimum part heat-up rate	1	> 0.5	(F/min)
Maximum part heat-up rate	5	< 10	(F/min)
Minimum time at final cure temperature	360	> 1	(min)
Maximum time at final cure temperature	380	< 720	(min)
Minimum peak resin temperature	100	> 100	(F)
Maximum peak resin temperature	365	< 800	(F)
Maximum acceptable heat-up gradient	50	< 150	(F/in)
Maximum acceptable cool-down gradient	50	< 150	(F/in)
Minimum resin cool down rate	1.5	> 0.5	(F/min)
Maximum resin cool down rate	5	< 10.0	(F/min)

Run

Done Local intranet

Detail of RDCS project generated by the AIM-C Producibility module



Notes:

-Positive constraint values indicate feasible design

- The amount of constraint violation is normalized with the response limit; Criticality of different constraints can be compared.

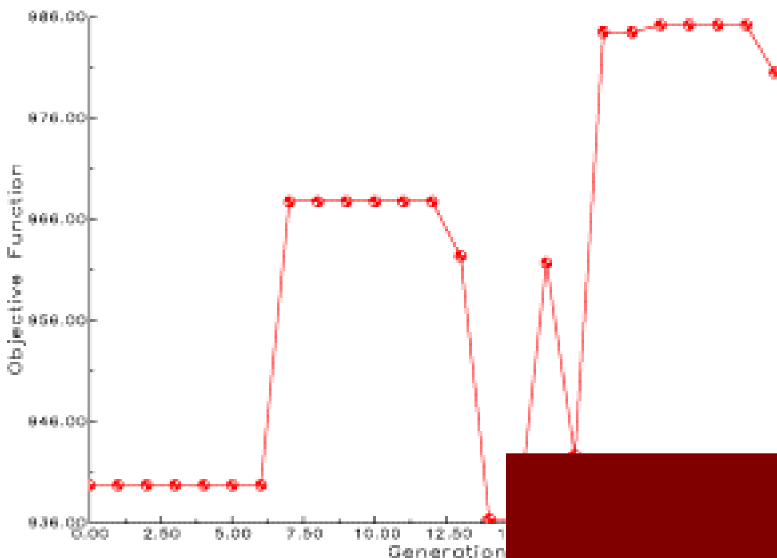
Results Summary

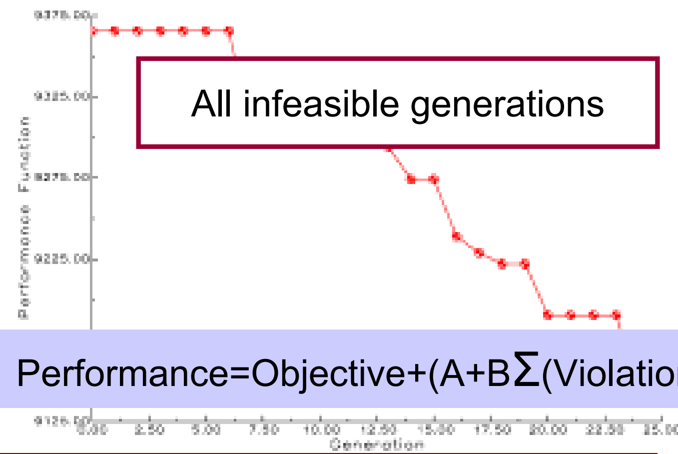
	Input Requirement	Units	Case 1	Case2	Case 3.	Case 1A
G	Part Thickness	Inches	0.25	2	2	0.25
H	Top Tool Thickness (3)	Inches	3	0	3	3
I	Tool Thickness	Inches	3	0.5	3	3
J	Tool Material (5)		Composite <3>	Composite <3>	Composite <3>	Aluminum <2>
K	Autoclave Pressure	Psi	85	85	85	85

Acceptable solution not obtained for Cases 1, 2, and 3
Not Producible given process bounds.

Case 1 rerun with Aluminum tooling (Case 1A)
Acceptable process found

Summary of Case 1





All infeasible generations

Performance=Objective+(A+BΣ(Violations))

<u>Violated constraints</u>

2 - Minimum part heat-up rate

4 - Minimum part heat-up rate at ramp 2

6 - Minimum time at final cure temperature

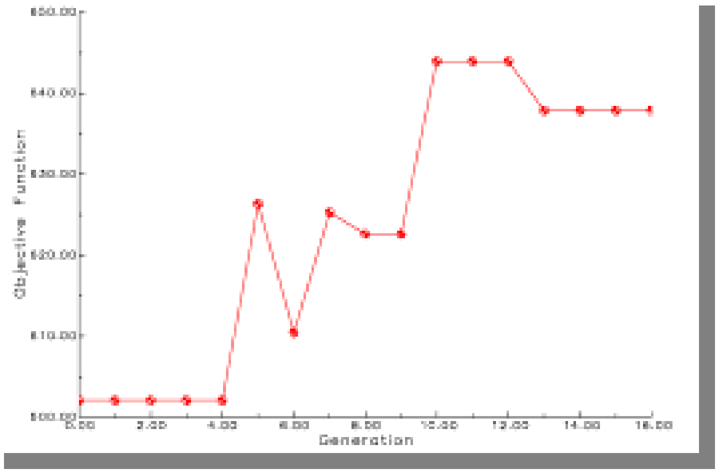
9 - Minimum peak resin temperature

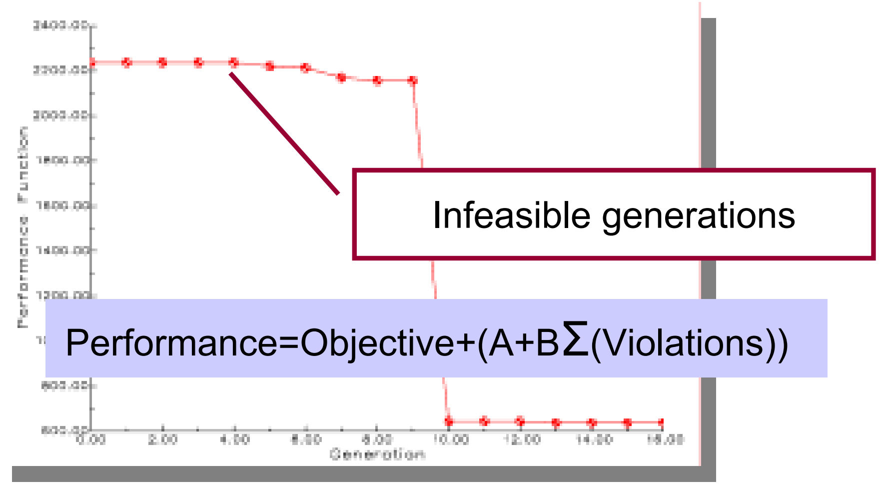
10 - Maximum acceptable heat-up gradient

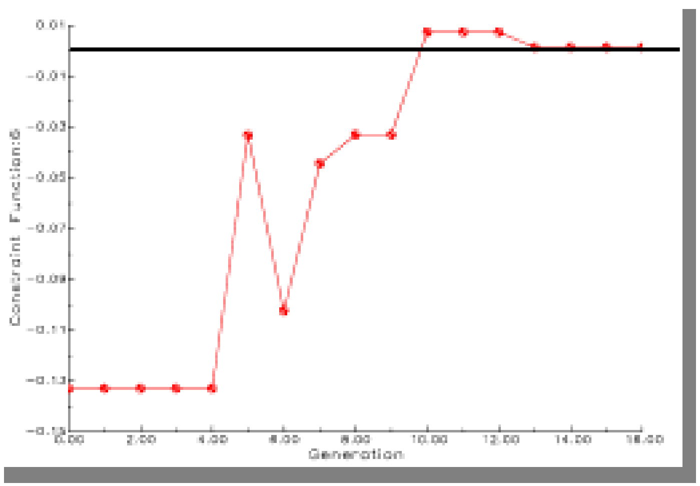
11 - Maximum acceptable cool-down gradient

12 - Minimum resin cool down rate

Summary of Case 1A







Important constraints

4 - Minimum part heat-up rate at ramp 2

5 - Maximum time at final cure temperature

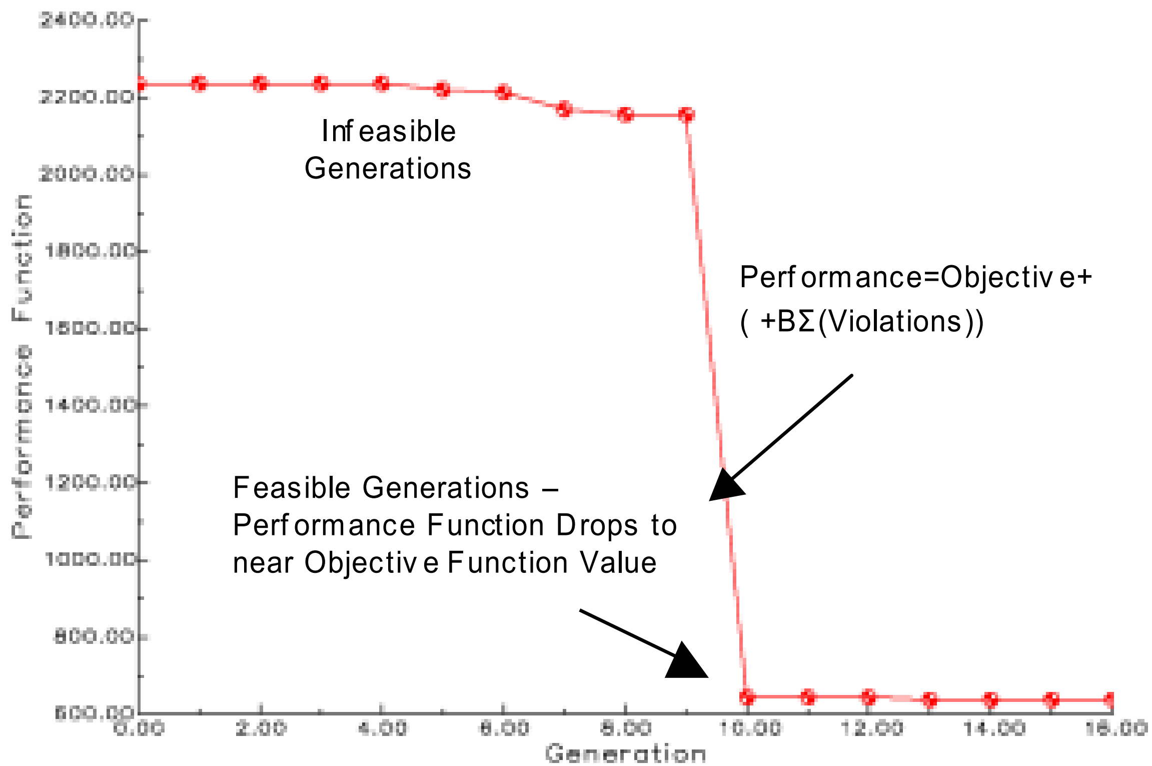
6 - Minimum time at final cure temperature

7 - Maximum acceptable heat-up gradient

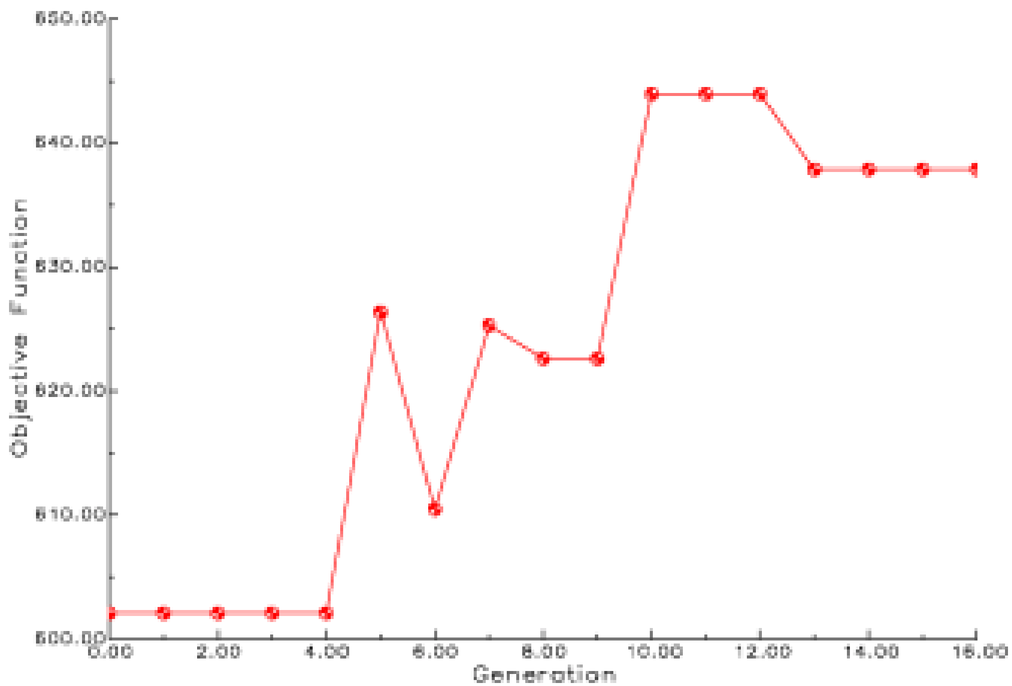
Resource needs: ~ 550 evaluations

3 hrs wall clock time (100 workstations)

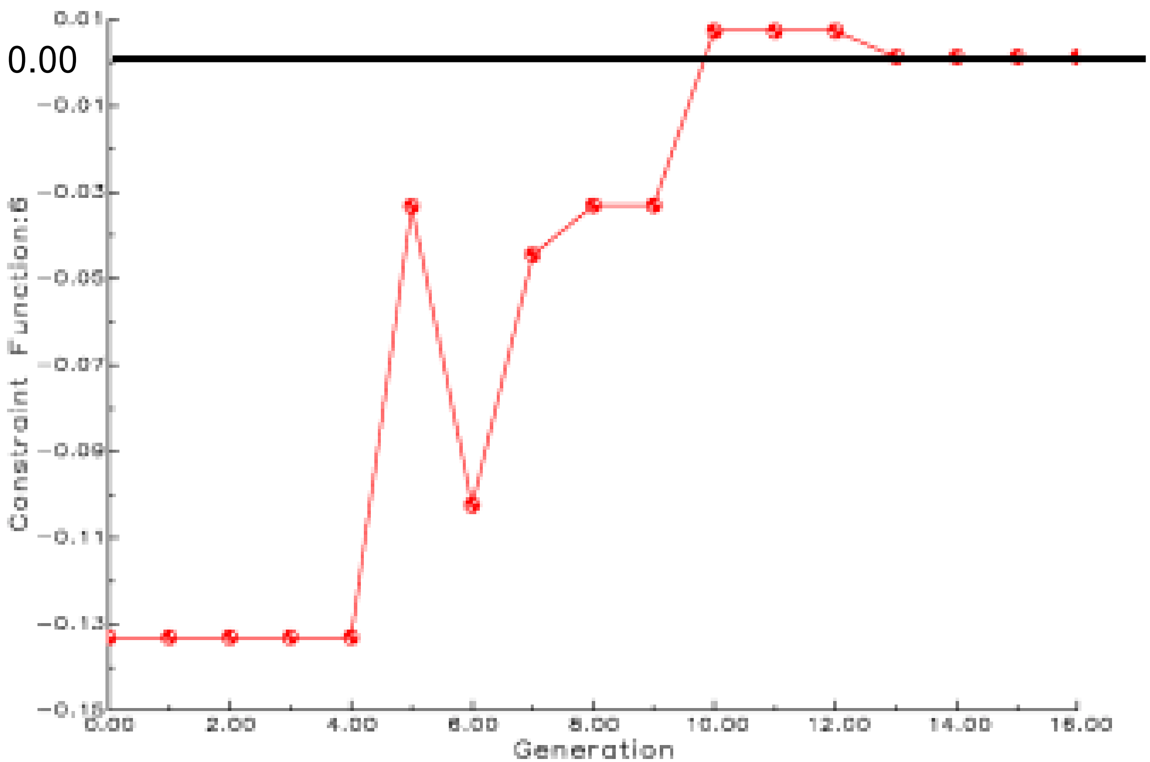
RDCS Genetic Algorithm Performance Function Vs. Generation for Case 1A



RDCS Genetic Algorithm Objective Function vs. Generation for Case 1A



RDCS Genetic Algorithm Constraint Function 6 (minimum time at final cure) vs. Generation for Case 1A



Case 1A Results- Comparison to Constraint

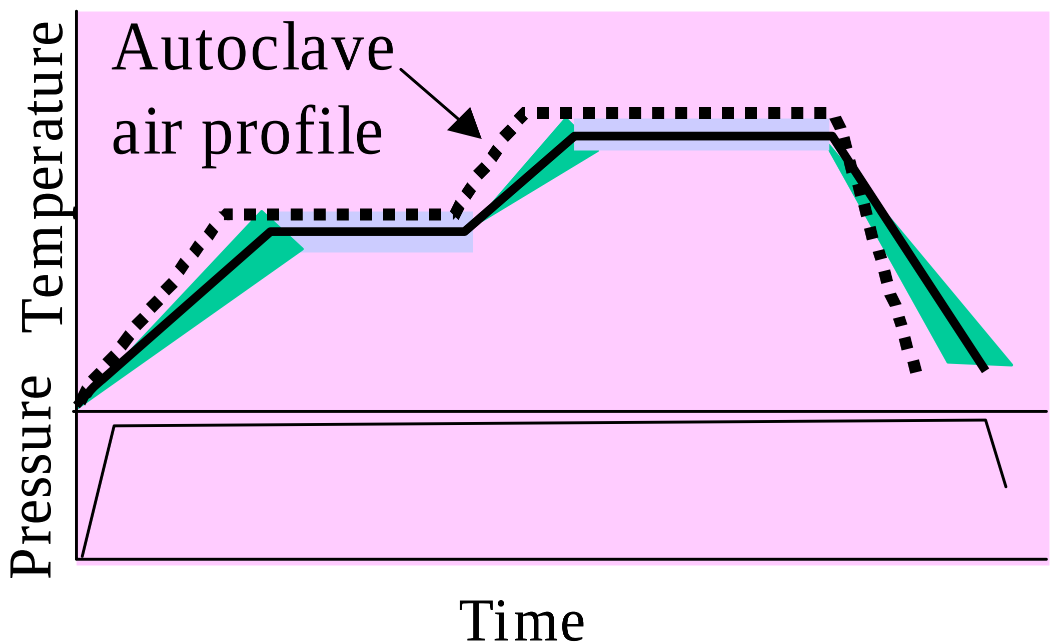
Input Requirement (Constraints)	Units	Min. Constraint	Min	Max	Max. Constraint
Acceptable part heat up rate	F/min	1	1.8259	1.8683	5
Acceptable time at final cure temperature	Minutes	360	360.46	377.74	380
Resin maximum acceptable Temperature	F	345		362.2	365
Maximum acceptable heat up gradient	F	0		24.1 R1 11.8 R2	50
Maximum acceptable cool down gradient	F	0		29.6	50
Resin acceptable cool down rate	F/min	-1.5	-2.643	-2.5468	-5

R1 - First Ramp
R2 – Second Ramp

Case 1A Results- Autoclave Air Temperature Profile

Input Requirement (Process Bounds)	Units	Demo Min.	Case 1A	Demo Max.
Ramp1 Rate (air)	F/min	2	7.119	10
Hold 1 Temperature	F	270	273.45	290
Hold 1 Time (air) (4)	Min	0	6.385	120
Ramp 2 Rate (air)	F/min	2	8.627	10
Hold 2 Temperature	F	355	362.42	365
Hold 2 Time (air)	Min	360	361.83	380
Ramp 3 (air)	F/min	-2	-7.059	-10

Notional Depiction of Cure Profile to Meet Requirements for Case 1A



Process cycle developed such that all areas of part meet constraints

Summary

•Integrated Producibility-Compro-RDCS design tool has been demonstrated

•Tool was used to search for feasible cure cycles

•Feasible designs were not found in all cases

–Insight into the process

–Options: change tooling material or relax constraints

–This is precisely what the AIM-C facilities are intended for:

Identify and solve design/producibility problems early to avoid cost and schedule overruns

Future Work

- Evaluate cases 2 and 3 with Aluminum, Invar tools
- Evaluate thin part on thin tooling
- Improve Producibility – RDCS Linkage
- Display RDCS results without RDCS GUI
- Investigate uncertainty analysis/robust design
- Effects of materials properties, heat transfer characteristics

Integration Structure and Proposed Improvements